Science of the Total Environment 636 (2018) 699–708

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Long-term straw decomposition in agro-ecosystems described by a unified three-exponentiation equation with thermal time

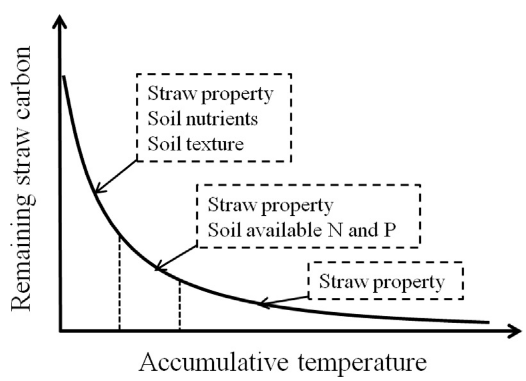
Andong Cai [a,b], Guopeng Liang [b], Xubo Zhang [c], Wenju Zhang [a], Ling Li [a], Yichao Rui [d], Minggang Xu [a,*], Yiqi Luo [b,e]

[a] National Engineering Laboratory for Improving Quality of Arable Land, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[b] Center for Ecosystem Science and Society, Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ 86011, USA
[c] Key Lab of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100081, China
[d] Department of Soil Science, University of Wisconsin-Madison, Madison, WI 53705, USA
[e] Department of Earth System Science, Tsinghua University, Beijing, China

HIGHLIGHTS

- Long-term straw decomposition driven by temperature and straw quality
- The remaining carbon of six straw has difference under one thermal year.
- The effects of soil property on the straw decomposition differ at different stages.
- The amount of remaining straw C was 29.41 Tg under one thermal year.
- Temperature increase of 2 °C could reduce the remaining straw C by 1.78 Tg.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 January 2018
Received in revised form 13 March 2018
Accepted 23 April 2018
Available online 1 May 2018

Editor: Baoliang Chen

Keywords:
Straw decomposition
Straw properties
Soil properties
Climate
Agro-ecosystem

ABSTRACT

Understanding drivers of straw decomposition is essential for adopting appropriate management practice to improve soil fertility and promote carbon (C) sequestration in agricultural systems. However, predicting straw decomposition and characteristics is difficult because of the interactions between many factors related to straw properties, soil properties, and climate, especially under future climate change conditions. This study investigated the driving factors of straw decomposition of six types of crop straw including wheat, maize, rice, soybean, rape, and other straw by synthesizing 1642 paired data from 98 published papers at spatial and temporal scales across China. All the data derived from the field experiments using little bags over twelve years. Overall, despite large differences in climatic and soil properties, the remaining straw carbon (C, %) could be accurately represented by a three-exponent equation with thermal time (accumulative temperature). The lignin/nitrogen and lignin/phosphorus ratios of straw can be used to define the size of labile, intermediate, and recalcitrant C pool. The remaining C for an individual type of straw in the mild-temperature zone was higher than that in the warm-temperature and subtropical zone within one calendar year. The remaining straw C after one thermal year was 40.28%, 37.97%, 37.77%, 34.71%, 30.87%, and 27.99% for rice, soybean, rape, wheat, maize, and other straw, respectively. Soil available nitrogen and phosphorus influenced the remaining straw C at different decomposition stages. For one calendar year, the total amount of remaining straw C was estimated to be 29.41 Tg and future temperature increase of 2 °C could reduce the remaining straw C by 1.78 Tg. These findings confirmed the long-term

* Corresponding author.
E-mail address: xuminggang@caas.cn (M. Xu).

https://doi.org/10.1016/j.scitotenv.2018.04.303

straw decomposition could be mainly driven by temperature and straw quality, and quantitatively predicted by thermal time with the three-exponent equation for a wide array of straw types at spatial and temporal scales in agro-ecosystems of China.

1. Introduction

Increasing atmospheric carbon dioxide (CO_2) concentration is expected to contribute to global warming (Smith and Fang, 2010; Tian et al., 2016). Previous work has suggested that agricultural soils can serve as a potential sink for atmospheric CO_2 by sequestrating soil carbon (C) (Lal, 2004; Schmidt et al., 2011). Crop residues such as wheat straw are a global resource with potential for contributing to soil C stocks and mitigating climate change (Liu et al., 2014; Lu, 2014). Straw return not only directly increases C input into the soil, but also improves soil physical and biochemical properties that are essential to crop growth (Lal, 2008; Liu et al., 2014). The rate of straw decomposition determines how fast the CO_2 is returned to atmosphere and ultimately the soil C stocks. Therefore, understanding the drivers of straw decomposition is critical for adjusting the accuracy of climate change models, mitigating climate change, and preserving ecosystem functions (Lin, 2014; Luo et al., 2015).

Straw decomposition is primarily controlled by the climate conditions, straw quality, and soil properties (Wang et al., 2012). Climate conditions such as temperature and precipitation are critical factors that control the straw decomposition on a large geographical scale (Gregorich et al., 2016). Many studies have found a strong linear relationship between the decomposition rate constant and mean temperature (Zhang et al., 2008; Wang et al., 2012). At ten sites spanning a 3500-km transect across the agricultural regions of Canada, Gregorich et al. (2016) found thermal time (accumulative temperature) accurately described kinetics of straw decomposition over five years. The different straw quality has long been thought to determine the decomposition rates (Wang et al., 2012). Using compound-specific isotopic analysis, molecules predicted to persist in soils (such as lignin or lipid) has been shown to turn over more slowly than the labile compounds (such as sugars) (Schmidt et al., 2011). The effect of properties such as soil nutrients and texture to the straw decomposition rate is indirect (Zhang et al., 2008; Ge et al., 2013). Over the five years, soil organic C, soil texture, pH and moisture had minimal discernible influence on decomposition kinetics over five years (Gregorich et al., 2016). The decomposition rate was positively correlated with soil nutrients, in nutrient rich soil with fast rate and nutrients was easy to retention in early stages of decomposition (Ge et al., 2013). The effects of soil properties on the straw decomposition may differ at different decomposition stages. However, the responses of these factors to straw decomposition remain uncertain, especially at spatial and temporal patterns in agro-ecosystems.

Predicting straw decomposition is difficult because they not only relate to many interacting factors but also depend on the equations of choice (Prescott, 2010; Derrien and Amelung, 2011). Many empirical equations based on physical and chemical heterogeneity of the original material have been proposed to estimate straw decomposition (Feng and Li, 2001; Adair et al., 2008). Although these empirical equations have been widely used and provided useful information on straw decomposition and soil C cycling, the results are difficult to extrapolate under different conditions (Adair et al., 2008; Prescott, 2010). First, most studies involved one site or a low diversity of crop straw types and chemistries, making it less representative at larger scales (Gholz et al., 2000; Gregorich et al., 2016). Second, many studies were conducted for less than five years, which might be not long enough to reveal the dynamics of straw decomposition during later phases (Amin et al., 2013). Finally, due to different starting times of the various straw decomposition experiments, seasonal and high-frequency temperature variability cannot be neglected (Manzoni et al., 2012). Therefore, these factors should be considered when choosing the best equation and using big data both to accurately describe straw decomposition and to extrapolate to spatial patterns for different crop systems.

The characteristics of straw C fraction that remain in the soil after one calendar year are referred to as the humification coefficient, which is an indicator of remaining straw C. This humification coefficient is important for estimating the amount of stable organic C and soil C sequestration potential as well as evaluating the parameterization of models (Janssen, 1984; Galvez et al., 2012). Complete humification of organic material can be accomplished after one calendar year or more, since humification depends on the soil nutrient status, organic material properties, and climatic conditions (Guo and Lin, 2001; Cai and Qin, 2006). The humification coefficient is not a constant value for identical organic materials under different conditions. The results of different studies are usually difficult to compare and use. Therefore, understanding the humification coefficient value under different conditions is very important to better understanding of soil C cycling in agro-ecosystems.

In this study, we used a comprehensive dataset to accurately describe the long-term straw decomposition and characteristics at spatial and temporal patterns in agro-ecosystems. We explored the straw decomposition and characteristics from 1642 straw decomposition data points paired with daily temperature from 92 climatic stations of China, spanning different straw types, soil properties, and climate conditions. Our specific objectives were: (i) to quantify the effect of thermal time on the six common crop straw decomposition at agro-ecosystems; (ii) to compare the characteristic of six straw types decomposition among different climate zones, and (iii) to assess the relative importance of soil properties drivers of straw decomposition during the different decomposition stages.

2. Materials and methods

2.1. Literature search and data sources

We searched the Web of Science (http://apps.webofknowledge.com) and China Knowledge Resource Integrated Database (http://www.cnki.net/) for papers published on straw decomposition through December 2016. Specific keywords included “the remaining straw C” or “decomposition and cropland in China”. To avoid publication bias, the following criteria were established: (i) Agronomic field experiments were included, but incubation experiments were excluded; (ii) The reports clearly stated the specific timing of the remaining straw C in litterbags; (iii) The remaining straw C data were reported in the form of figures or tables (The data presented as equations were ignorEd.); (iv) At least three measurement values were included during experiments, and one of the values must be within one year; and (v) Experiments were not supplemented with anthropogenic factors, such as the addition of fertilizer, to accelerate or decelerate the buildup of remaining straw C.

From these studies, we directly obtained the remaining straw C percentages (%) as well as their corresponding times (from tables in those studies). Get Data Graph Digitizer 2.24 software was used to indirectly obtain data from the graphs. In these studies, the data were presented as the remaining straw C concentration instead of the percentage of remaining straw C. We estimated the percentage of remaining straw C according to the initial and remaining straw C densities. The data reported in terms of straw C decomposition were converted to the percentage of C remaining by taking the difference between 100 and the percentage of

C decomposition. In addition, we also recorded all available information that could be used as explanatory factors of the effects of remaining straw C, including climatic conditions, soil properties (texture and nutrients), and straw properties. Since most researchers did not report daily temperature data during their experiments, these data were obtained from climatic stations near the study sites via the meteorological sharing service system of China (http://cma.gov.cn/).

Overall, 98 published papers that met the above criteria were retrieved, resulting in a dataset that included 1642 remaining straw C data points paired with time and corresponding accumulated temperature (Fig. 1). These data spanned six categories according to straw type: wheat (341), maize (739), rice (192), soybean (180), rape (120), and others (70).

2.2. Compilation of the collected dataset

To accurately describe the remaining straw C dynamics, we compared one-, two-, and three- exponent equation to determine the number of C pools:

$$R_t = R_1 e^{-k_1 t} \tag{1}$$

$$R_t = R_1 e^{-k_1 t} + R_2 e^{-k_2 t} \tag{2}$$

$$R_t = R_1 e^{-k_1 t} + R_2 e^{-k_2 t} + R_3 e^{-k_3 t} \tag{3}$$

where R_t is the remaining straw C (%) at time t (year), R_p is the amount of each C pool ($P = 1, 2,$ or 3), and k_p is the decomposition rate of each C pool. We defined R_1 as the difference between 100% and the sum of R_2 and R_3 (thus, in the one-exponent equation, $R_1 = 100\%$, while in the two-exponent equation, $R_1 = 100\% - R_2$). Modified Akaike's information criterion (AICc) was used to select the candidate equations (Burnham, 2002). This methodology also provides information on equation selection uncertainty by calculating Akaike weights (w_r) for each equation (Burnham, 2002).

The thermal time was used to describe the patterns of remaining straw C dynamics. The concept of thermal time has been used as a way of adjusting time to account for temperature effects on the rate of biological processes (Yousefi et al., 2014; Gregorich et al., 2016). Briefly, the thermal time was calculated on the basis of the accumulated daily degree-days (base temperature of 0 °C) from the date of initial straw application; atmosphere temperature from nearby meteorological stations was used for these calculations. One thermal year was converted to accumulate temperature of 3652.5 °C (Gregorich et al., 2016). To demonstrate the implications of our findings, remaining straw C concentration and amount were predicted under future climate warming based on the IPCC (2014). One representative scenario (temperature increase of 2 °C) was selected to predict the remaining straw C concentration and amount.

The method of Zhang et al. (2014), which involved co-kriging and kriging classifications combined with regression, was used to obtain spatial predictions. The resulting datasets, which have a spatial resolution of $0.01 \times 0.01°$, have been made available. Based on agricultural statistics, investigating data of farmer and a number of data published in the literature, the amounts and utilization of crop straw were reported as described by Gao et al. (2009) and Wang et al. (2015). The regional level was selected as the spatial unit for both statistical calculations and mapping. Regional statistics for changes in straw C were calculated from the data generated by Monte Carlo simulations and were mapped. Therefore, the total remaining straw C and the release from the six types of straw were calculated as a baseline for future climate warming scenarios.

2.3. Statistics

Using the AICc, we tested the significant differences among the three equations that involved thermal time. Our results showed that the

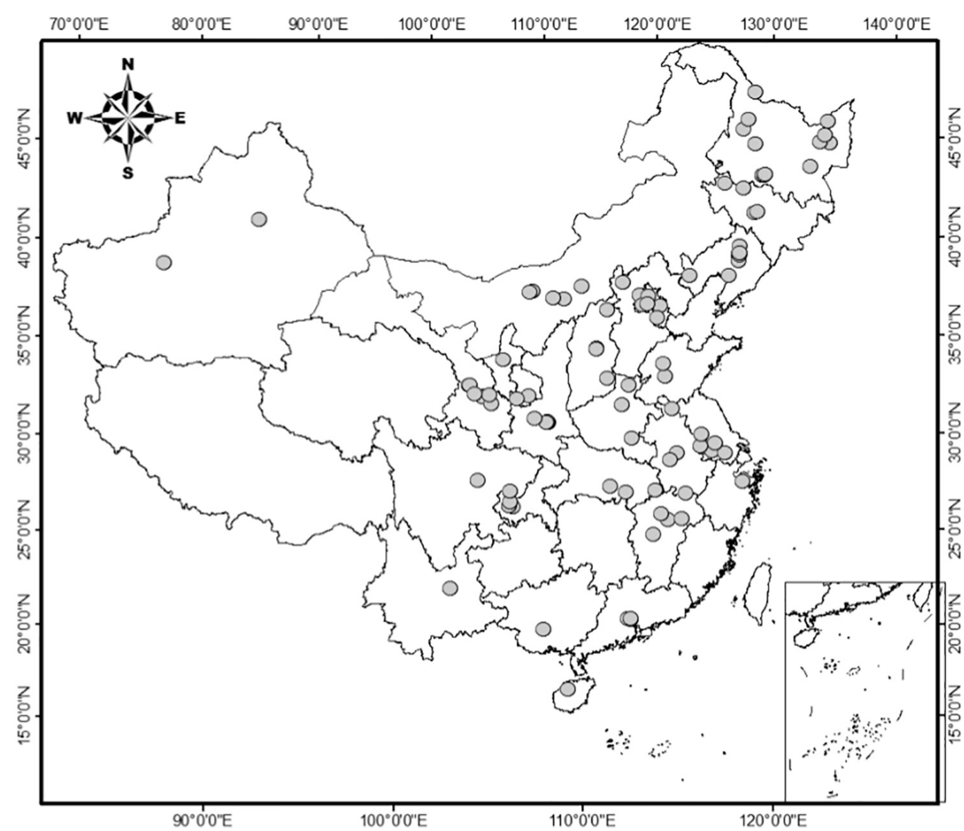


Fig. 1. Locations of the sites studied in this research.

relationships between remaining straw C and thermal time were fitted using the three-exponent equation for the six straw types. We used 90% of the data to fit the relationships between remaining straw C and thermal time, and the other 10% of the data were used to test the accuracy of the fitted equations. The relationships between the sizes of different C pools and straw chemical properties were evaluated with linear regression equations. In addition, we used residual values of the remaining C to explore the influence of soil properties on the remaining straw C. The amounts of remaining straw C in one calendar year and one thermal year were calculated under different temperature zones. All the equation fittings were performed using SigmaPlot 10.0 for Windows.

3. Results

3.1. Chemical characteristics of the six straw types

The C concentration of the six types of straw ranged from 412 g C kg^{-1} (rice) to 446 g C kg^{-1} (maize) (Table 1). The N and P concentration were significantly higher than in soybean straw than in the other five straw types. Compared with the soybean straw, the wheat, maize, rice, rape, and other straw was further characterized by a significantly higher C/N ratio in the order of wheat > rape > maize > rice > other. The cellulose and lignin contents were considerably higher in the wheat and rice straw, respectively, than in the other types of straw. The ratios of lignin/N and lignin/P were highest in the wheat straw (33.56) and rice straw (231), respectively, whereas the ratios of lignin/N and lignin/P were lowest in the soybean straw (1.08 and 4.17, respectively).

3.2. Selection of the best equation describing remaining straw C dynamics

Across all sites and straw types, the three-exponent equation was selected by the AICc as the best equation to describe the relationship between the remaining straw C and thermal time instead of calendar time (Table 2). This equation captured approximately 86% of the variability of the remaining straw C and consisted of three exponential decomposition rates (k_p): the labile, intermediate, and recalcitrant C pools. These equations showed labile ($k_1 > 5$), intermediate ($0.5 < k_2 < 5$), and recalcitrant decomposition ($k_3 < 0.5$) (Fig. 2). The other equations exhibited Δr values > 7 and w_r values < 0.01, indicating that this equation had essentially no support and virtually no chance of being chosen to describe the remaining straw C.

3.3. Remaining straw C dynamics of the six straw types

The remaining C dynamics of the six straw types significantly ($P < 0.01$) followed a three-exponent equation; the equations showed an initial rapid rate of C loss, which slowed as the thermal time increased (Fig. 2). The size of the intermediate C pool (average of 45%) was higher than that of the labile C pool (average of 37%) and recalcitrant C pool (average of 19%). The decomposition rate of the recalcitrant C pool was the lowest, ranged from 0.01 yr^{-1} for maize to 0.09 yr^{-1} for rape. The mean transit thermal time (1/k) of the recalcitrant C pool was the highest and ranged from 12 thermal years for rape to 70 thermal years for maize. The average decomposition rates of the labile and intermediate C pools were 15.95 yr^{-1} and 1.02 yr^{-1}, respectively. After one and ten thermal years, only 34.92% and 11.97% of straw C can be remained in soil (Fig. 2).

Straw quality profoundly impacted on the size of different C pools (Fig. 3). The size of the labile C pool significantly increased with increasing lignin/N and lignin/P ratios. The size of the intermediate C pool decreased in response to an increase in the lignin/P ratio but not in the lignin/N ratio. The lignin/N ratio was negatively correlated with the size of the recalcitrant pool and exhibited a slope of 0.36.

3.4. Systematic biases of remaining straw C

Residual analysis was performed to explore whether soil properties could explain the variance of the remaining straw C (Fig. 4). For one-half thermal year and one thermal year, the residual remaining C was significantly positively correlated with soil pH (Fig. 4d1–d2), soil clay content (Fig. 4f1), and soil silt content (Fig. 4f2). A significant negative linear correlation was recorded between the residual remaining C and the soil organic C, soil available N, soil available P (Fig. 4c2), and soil sand contents. For one and a half thermal year, only the soil available N and P affected the residual remaining C, explaining 28% and 27%, respectively (Fig. 4b3 and c3).

3.5. The characteristics of remaining straw C

The determination of temperature revealed different contributions of remaining C among the different straw types (Table 3). For one calendar year, the value of remaining C in the mild-temperature zone was higher than that in the warm-temperature and subtropical zones, and differences due to different straw types were recorded. The remaining C was highest for rice in the mild-temperature zone (41.13%) and lowest for maize in the subtropical zone (22.05%), indicating that these values were not constant for the same straw type within a single calendar year; hence, the humification coefficient was used. For one thermal year, the value of remaining C was a fixed value for the same straw type. The remaining C was highest in the rice straw (40.28%), followed by the soybean, rape, wheat, maize, and other straw. This finding indicates that the straw properties determined the value of C remaining (temperature was excluded).

3.6. Remaining straw C concentration and amount

The three-exponent equations and driving factors predicted that the current remaining straw C concentration was estimated to be 145.63 g kg^{-1} within one calendar year and was strongly spatially correlated, albeit with high variance (Fig. 5a). The greatest remaining C concentration (165.86 g kg^{-1}) was recorded in northern China; the least, in southern China (126.91 g kg^{-1}). According to the amount and utilization of straw, the total remaining straw C amount was 29.41 Tg (1 Tg = 10^{12} g) within one calendar year, although the amount differed by straw type, which followed the order of maize, rice, wheat, rape, soybean, and other straw. Under future temperature increase of 2 °C, the remaining straw C and released amounts were estimated to be 27.63 Tg

Table 1
Initial chemical characteristic of the six straw types.

Straw types	Carbon	Nitrogen	Phosphorus	C/N	Cellulose	Lignin	Lignin/N	Lignin/P
	g kg^{-1}				%			
Wheat	437	5.95	1.04	73.40	42.02	19.97	33.56	192
Maize	446	8.50	2.06	52.43	32.72	17.51	20.60	85
Rice	412	9.98	1.26	41.23	38.36	29.12	29.18	231
Soybean	422	15.29	3.94	27.62	37.97	16.44	10.75	42
Rape plant	425	6.99	1.57	60.90	38.62	21.47	30.72	137
Other	415	10.18	1.21	40.71	32.93	19.67	19.32	163

Table 2
Regarding the equations, compared with the one- or two-exponent equations, the three-exponent equation with thermal time more accurately predicted remaining straw carbon across the cropland datasets of China.

	Equations	No.	R^2	*P*	AICc	Δr	w_r	R1	R2	R3	k1	k2	k3
Calendar time	$R_t = R_1e^{-k1t}$	1642	0.65	<0.01	9299	1524	0.00	100.00			1.7712		
	$R_t = R_1e^{-k1t} + R_2e^{-k2t}$	1642	0.75	<0.01	8510	735	0.00	42.56	57.44		7.2416	0.2464	
	$R_t = R_1e^{-k1\ t} + R_2e^{-k2t} + R_3e^{-k3t}$	1642	0.83	<0.01	7896	121	0.00	21.89	48.99	29.12	35.4452	3.1557	0.1372
Themal time	$R_t = R_1e^{-k1t}$	1642	0.67	<0.01	9151	1376	0.00	100.00			1.3333		
	$R_t = R_1e^{-k1t} + R_2e^{-k2t}$	1642	0.79	<0.01	8260	485	0.00	50.95	49.05		7.7231	0.3002	
	$R_t = R_1e^{-k1\ t} + R_2e^{-k2t} + R_3e^{-k3t}$	1642	0.86	<0.01	7775	0	1.00	29.59	45.26	25.16	21.8055	1.4833	0.0637

and 1.78 Tg in one calendar year, respectively, although the amounts differed by straw type (Fig. 5b and c). The average released straw C concentration was 10.55 g kg^{-1}; specifically, the average was 13.25 kg^{-1} for northern China and 7.25 kg^{-1} for southern China. The remaining straw C amount released under future climate warming conditions could be 6% of the current amount in one calendar year.

4. Discussion

4.1. Evaluation of the remaining straw C dynamics

Understanding the remaining straw C dynamics is crucial for improving soil physical and biochemical properties, adjusting model accuracy

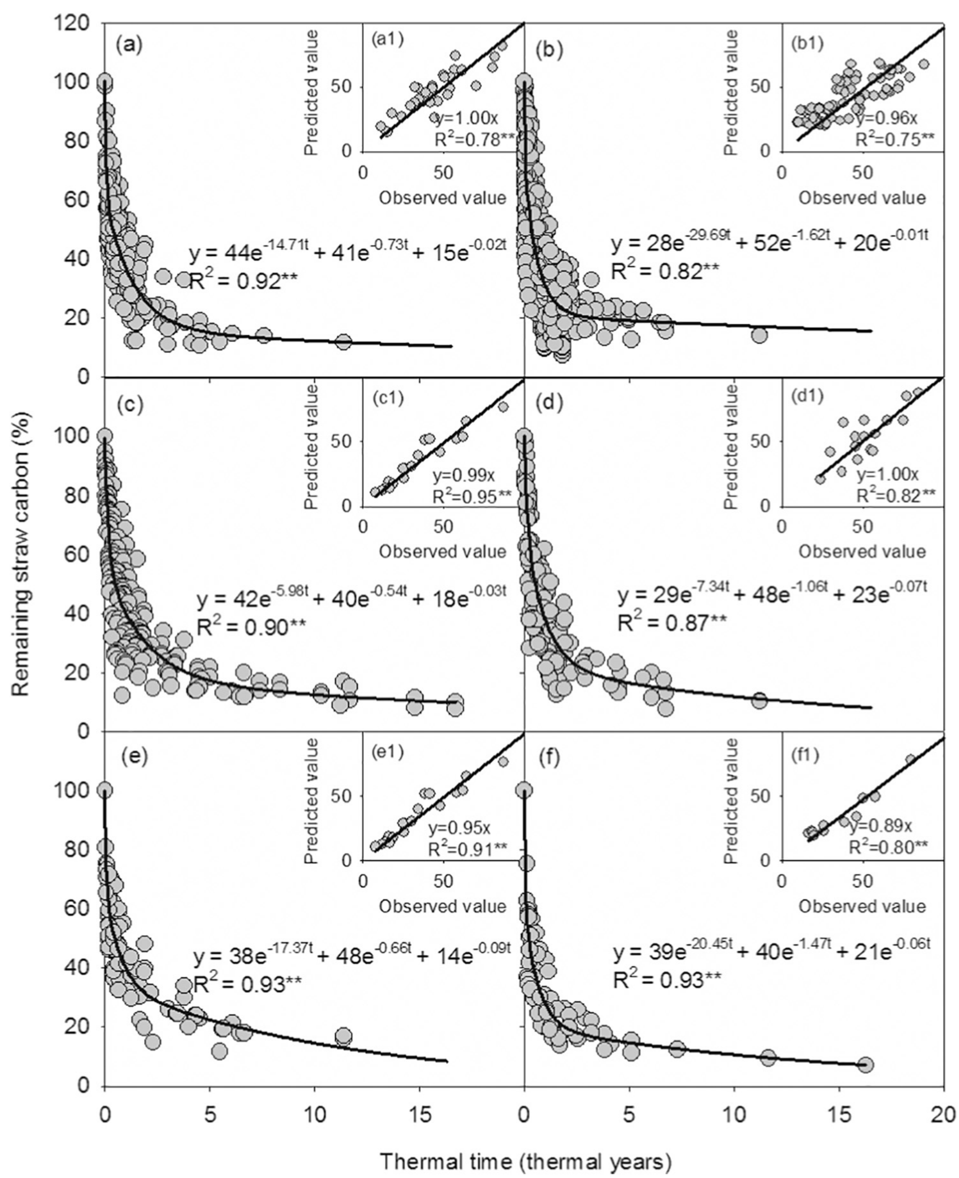


Fig. 2. The three-pool equation with thermal time provided the most accurate predictions of the remaining carbon (%) for the six straw types for across croplands in China. a, wheat; b, maize; c, rice; d, soybean; e, rape plant; f, other species. ** indicates a significant correlation at $P < 0.01$. Note: Ninety percent of the data were used to fit equations (a–f), and 10% of the data were used to test the accuracy of the fitted equations (a1–f1).

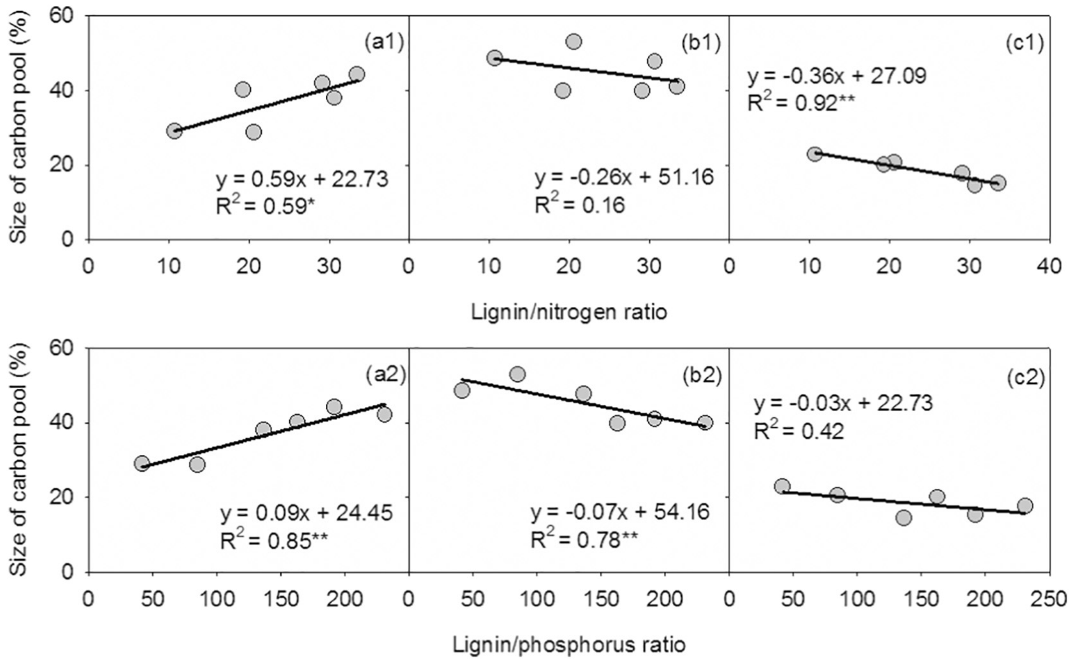


Fig. 3. Relationships between the sizes of labile carbon pool (a), intermediate carbon pool (b), and recalcitrant carbon pool (c) with the lignin/nitrogen ratio and the lignin/phosphorus ratio from three-pool equation of remaining straw carbon. * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively.

and predictability, mitigating climate warming, and preserving the health of terrestrial ecosystems (Lal, 2008; Liu et al., 2014; Luo et al., 2015). The duration of remaining straw C experiments is particularly important for understanding actual remaining straw C dynamics at later stages. Studies involving short-term experiments (less than five years) have reported that remaining straw C dynamics are adequately described by single-exponent equation (Wang et al., 2011; Wang et al., 2012). For medium-term experiments (more than five years but less than ten years), two-exponent equation often better describes the remaining straw C dynamics over time (Gregorich et al., 2016). In addition, many studies have demonstrated that temperature is a major factor that influences remaining straw C (Wang et al., 2012; Bradford et al., 2016). In the field, because of differences in the start times of experiments investigating remaining C, seasonal and high-frequency temperature variability cannot be neglected (Manzoni et al., 2012). Therefore, thermal time instead of calendar time was used to normalize the different data to the same start time. Our dataset allowed the measurement of remaining straw C under diverse and fluctuating conditions observed in the field. A three-exponent equation with thermal time described reasonably well the remaining straw C for long-term experiments (>10 years). This result was consistent with that of Adair et al. (2008), who used the same three-exponent equation. In theory and according to the equation performances, the three-exponent equation with thermal time accurately described the remaining straw C dynamics across large spatial and temporal scales.

The three-exponent equation incorporates C pools of varying decomposition rates and turnover times (Erhagen et al., 2013). Carbon pools can be controlled by a wide variety of organic material-related qualities, including the N concentration, P concentration, and lignin content (Gusewell and Freeman, 2005; Zhang et al., 2008). Compared with labile compounds (such as sugars) in soils, which persist for only a few weeks, the recalcitrant compounds of organic materials (such as lignin) can require decades to decompose (Schmidt et al., 2011). In agreement with the results of those studies, our results showed that the average decomposition rates of the labile, intermediate and recalcitrant C pools were 15.95, 1.02, and 0.05 yr^{-1}, respectively. The mean thermal time (1/k) turnover of the recalcitrant C pool was 12 thermal years for rape and 70 thermal years for maize. However, the decomposition rate of the labile pool (15.95 yr^{-1}) was significantly higher than that reported by Adair et al. (2008) (3.55 yr^{-1}), who used the three-exponent equation to assess forest soils. Forest organic materials have a relatively low initial N concentration, and crop straw has a relatively high N concentration (Table 1) (Adair et al., 2008); therefore, labile compounds with a higher N concentration and lower lignin content will rapidly decompose. We also found that the lignin/N ratio was positively correlated with the size of the labile C pool (Fig. 3). These results were inconsistent with those of previous studies (Hobbie, 2005; Adair et al., 2008). As the lignin/N ratio increases (given an initial lignin/N ratio > 60), the size of the labile mass first decreases rapidly but then decreases more slowly as the lignin/N ratio approaches 60 (Adair et al., 2008). In our study, the lignin/N ratio was <40 (Table 1). Under a lower lignin/N ratio, lignin is not among the basic on compounds in the remaining straw C.

4.2. Soil properties can impact on remaining straw C dynamics

The results of the residual analysis showed that the influence of the initial soil organic C content, soil pH, and soil texture gradually decreased and that the influences of the soil available N and P gradually increased for the residual remaining C as the thermal years increased (Fig. 4). The influences of the soil available N and P on the remaining straw C dynamics reflect microbial effects (for example, lower C/N and C/P ratios or greater efficiency) (Cotrufo et al., 2013). Thus, in the early stages of remaining straw C dynamics, soil available N and P induce changes in microbial community attributes, and these changes reduce the response of remaining straw C to increased soil nutrients (Gusewell and Freeman, 2005). However, Gregorich et al. (2016) reported that soil properties had a minimal discernible influence on remaining C rates based on 10 sites across agricultural regions. On the other hand, our results were based on the agro-ecosystems of China, which have lower soil nutrient contents (Zhu, 2008). Soil available N and P are not limiting factors for remaining straw C in soils rich in available N and P concentrations (Hobbie, 2005). Therefore, the accuracy of the three-exponent equation can be further improved via soil properties, especially soil available N and P. Nonetheless, the following two aspects should be further considered to better understand the remaining straw C in the soil. First, soil nutrients will change as the experiment progresses. Although a relationship was recorded between the initial

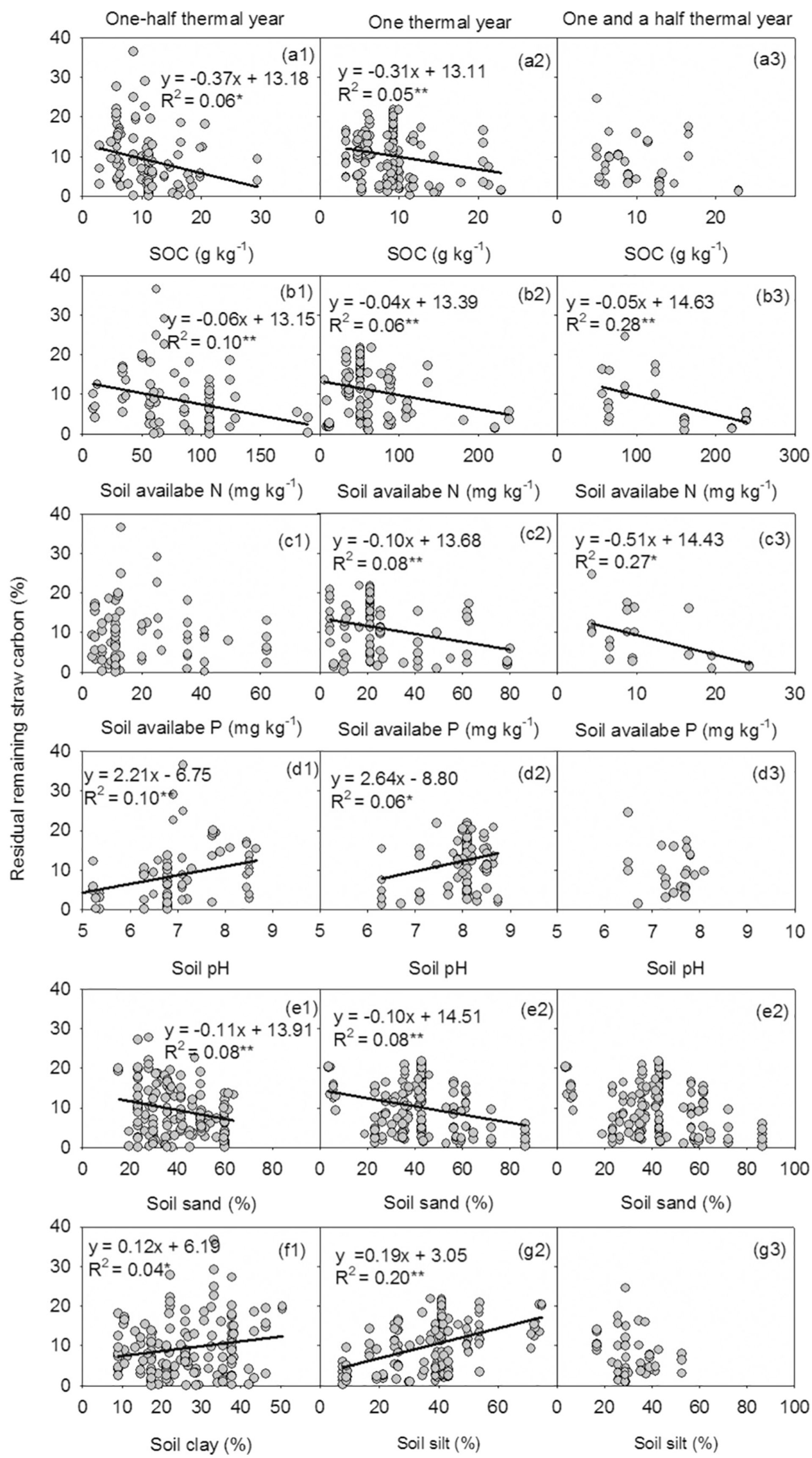


Fig. 4. Residual straw carbon remaining under different thermal years versus initial soil organic carbon (SOC) (a), initial soil available nitrogen (N) (b), initial soil available phosphorus (P) (c), initial soil pH (d), soil sand content (e), soil silt content (f), and soil clay content (g). * and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively.

Table 3
Remaining carbon (%) of six straw types under one calendar year and one thermal year.

Straw type	1 calendar year			1 thermal year
	MT	WT	S	
Wheat	36.01	31.68	26.75	34.71
Maize	31.42	28.73	22.05	30.87
Rice	41.13	35.03	32.00	40.28
Soybean	38.84	34.61	24.47	37.95
Rape plant	38.74	35.03	30.51	37.77
Others	28.69	23.93	23.51	27.99

Note: MT, mild-temperature zone; WT, warm-temperature zone; S, subtropical zone.

soil nutrients and the residual C remaining at different stages, the relationship between soil nutrient dynamics and remaining straw C dynamics remains unclear. Second, soil temperature is an effective factor for describing remaining straw C dynamics. However, these data could not be obtained from published papers or the meteorological sharing service system. Therefore, the effect of soil temperature on remaining straw C dynamics should be investigated in future research.

4.3. Limitations of the humification coefficient

The results of our study demonstrated significant differences for humification coefficients in response to different straw types and climatic conditions (Table 3). Similar results were also reported by Wang et al. (2016), in that humification coefficients were significantly affected by the type of organic material and agricultural region. With respect to organic material-related qualities, the lignin content determines the humification coefficient (Klotzbücher et al., 2011). We also report that the humification coefficient and lignin content of rice straw were the highest among all straw types in different temperature zones. Bayer et al. (2006) assumed that the humification coefficient was constant for a given organic material type and soil tillage system. Nicoloso et al. (2016) reported that humification coefficients significantly differed under different soil management practices. Overall, the humification coefficient was mostly regulated by organic material quality, soil properties, and climatic factors. This finding means that the humification coefficients reported in different studies are difficult to compare and apply. Some researchers have tried to calculate the humification coefficient based on an average annual temperature of 10 °C (Bradbury et al., 1993; Cayuela et al., 2010). By the same method, we calculated the remaining C from different straw types based on one thermal year (accumulated annual temperature of 3652.5 °C); these values followed the order of rice > soybean > rape > wheat > maize > and other straw. In agreement with the results reported by Gregorich et al. (2016), the remaining straw C of wheat was approximately 35% in one thermal year. Therefore, this approach better reflected the remaining C characteristics because the temperature factor was excluded. The next step should

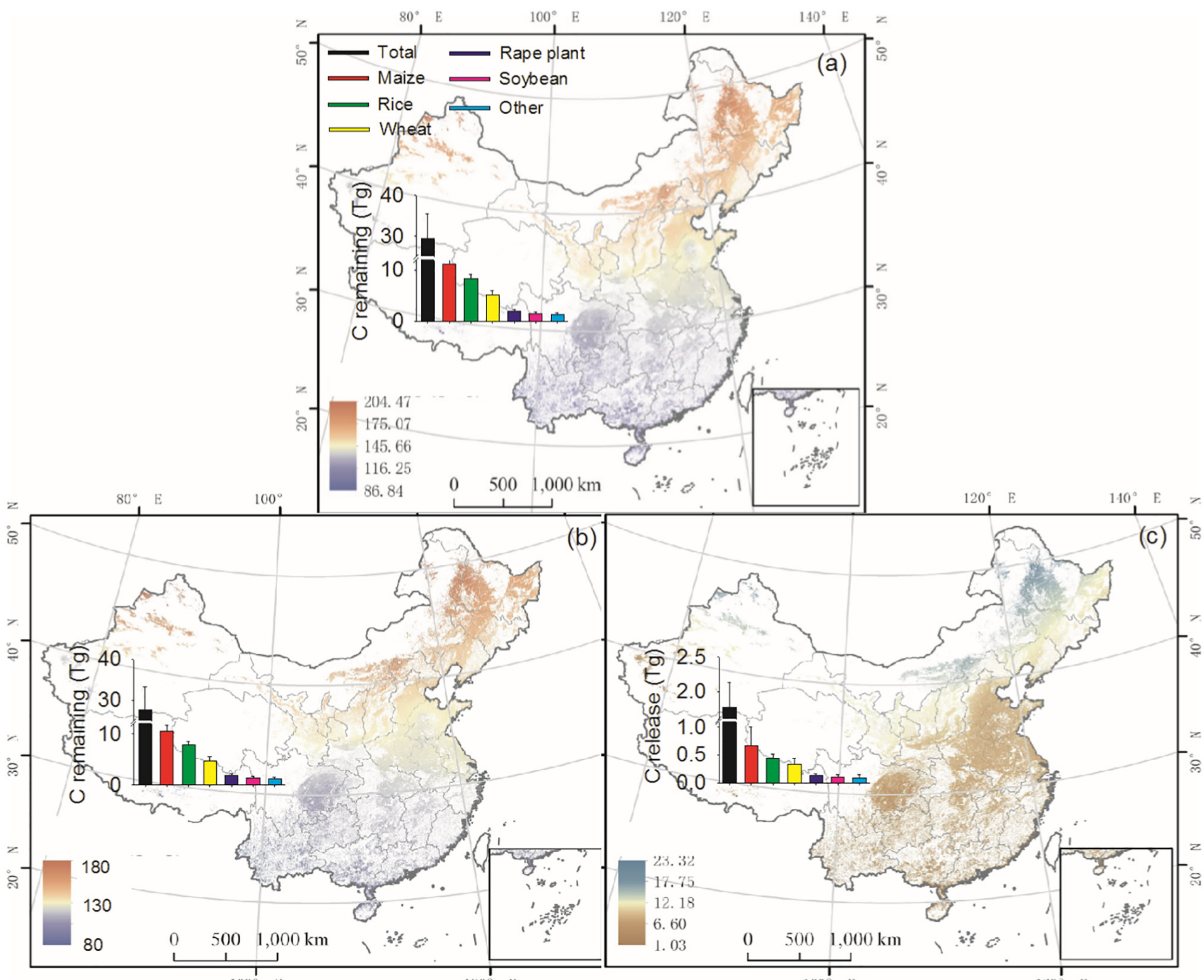


Fig. 5. Current remaining straw carbon concentration and amount (g kg^{-1}, a) as well as the predicted remaining carbon (C) concentration (g kg^{-1}, b) and released carbon density (g kg^{-1}, b) under future climate warming conditions (2081–2100, temperature increase of 2 °C for RCP6.0) in one calendar year.

involve the accurate exploration of the remaining straw C characteristics (in one thermal year) under different soil types.

4.4. Estimation of the remaining straw C amount

Based on the amount and utilization of crop straw and the remaining straw C dynamics, the current remaining straw C amount was determined to be 29.41 Tg (1 Tg = 10^{12} g) in one calendar year. The remaining straw C amount in our results was slightly lower than that in other reports from China (Sun et al., 2010; Lu, 2014). Because of the assumption that all straw was inputted into the soil, the results of those studies are overestimated (Sun et al., 2010; Lu, 2014). The remaining straw C amount for maize, rice, and wheat accounted for 83% of the total remaining straw C amount in one calendar year; maize, rice, and wheat are the main crops in China and produce 38.2%, 23.9% and 15.1% of the total straw amount, respectively (Gao et al., 2009). Worldwide, approximately 34.4 Tg yr^{-1} of crop straw is produced, which could lead to the sequestration of 200 Tg C yr^{-1} (Lal, 1997). The contribution of straw from China to global soil C sequestration from straw is approximately 15%. The remaining straw C amounts in China are higher than those in Europe and the United States (Smith et al., 2000; Follett, 2001). The remaining straw C amounts account for 1.35% of the C emissions from fuel use (2.18 Pg) in China. The report by the IPCC predicted a global surface temperature increase of 2 °C (RCP 6.0) by the end of the 21st century (2081–2100) (IPCC, 2014). This increase may result from the additional release of greenhouse gases from terrestrial ecosystems in response to climate warming (Sarmiento, 2000). Under future climate warming conditions, our results support the view that the amount of straw C release would increase by 1.78 Tg, which accounts for 6% of the amount of the remaining straw C in one calendar year.

5. Conclusions

The results of this study clearly demonstrated that thermal time and straw qualities are the key factors that regulate straw decomposition. The remaining C for an individual type of straw in the mild-temperature zone was higher than that in the warm-temperature and subtropical zones in one calendar year. The remaining C from different straw types in one thermal year followed the order of rice, soybean, rape, wheat, maize, and other straw. Both thermal time and three-exponent equation provided the most accurate predictions of the long-term straw decomposition in agro-ecosystems. The accuracy of the three-exponent model could be further improved by incorporating soil properties, especially soil available N and P concentrations. Compared with the humification coefficient, the index of remaining straw C in one thermal year better reflected the remaining straw C characteristics (temperature was excluded). Future climate warming may accelerate the straw decomposition rate in the agro-ecosystems of China.

Acknowledgments

Financial support from the National Natural Science Foundation of China (41571298, 41620104006 and U1710255) is gratefully acknowledged. We thank the authors whose data and work were included in our meta-analysis. We are grateful to the anonymous reviewers for their insightful comments, which greatly improved the manuscript.

References

Adair, E.C., Parton, W.J., Del Grosso, S.J., Silver, W.L., Harmon, M.E., Hall, S.A., Burke, I.C., Hart, S.C., 2008. Simple three-pool model accurately describes patterns of long-term litter decomposition in diverse climates. Glob. Chang. Biol. 14, 2636–2660.

Amin, B.A.Z., Chabbert, B., Moorhead, D., Bertrand, I., 2013. Impact of fine litter chemistry on lignocellulolytic enzyme efficiency during decomposition of maize leaf and root in soil. Biogeochemistry 117, 169–183.

Bayer, C., Lovato, T., Dieckow, J., Zanatta, J.A., Mielniczuk, J., 2006. A method for estimating coefficients of soil organic matter dynamics based on long-term experiments. Soil Tillage Res. 91, 217–226.

Bradbury, N.J., Whitmore, A.P., Hart, P.B.S., Jenkinson, D.S., 1993. Modelling the fate of nitrogen in crop and soil in the years following application of 15N-labelled fertilizer to winter wheat. J. Agric. Sci. 121, 363–379.

Bradford, M.A., Berg, B., Maynard, D.S., Wieder, W.R., Wood, S.A., Cornwell, W., 2016. Understanding the dominant controls on litter decomposition. J. Ecol. 104, 229–238.

Burnham, K.P., 2002. Information and Likelihood Theory: A Basis for Model Selection and Inference. Springer New York.

Cai, Z.C., Qin, S.W., 2006. Dynamics of crop yields and soil organic carbon in a long-term fertilization experiment in the Huang-Huai-Hai Plain of China. Geoderma 136, 708–715.

Cayuela, M.L., Oenema, O., Kuikman, P.J., Bakker, R.R., Van Groenigen, J.W., 2010. Bioenergy by-products as soil amendments? Implications for carbon sequestration and greenhouse gas emissions. GCB. Bioenergy 2, 201–213.

Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, E., 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Glob. Chang. Biol. 19, 988–995.

Derrien, D., Amelung, W., 2011. Computing the mean residence time of soil carbon fractions using stable isotopes: impacts of the model framework. Eur. J. Soil Sci. 62, 237–252.

Erhagen, B., Oquist, M., Sparrman, T., Haei, M., Ilstedt, U., Hedenstrom, M., Schleucher, J., Nilsson, M.B., 2013. Temperature response of litter and soil organic matter decomposition is determined by chemical composition of organic material. Glob. Chang. Biol. 19, 3858–3871.

Feng, Yongsheng, Li, Xiaomei, 2001. An analytical model of soil organic carbon dynamic based on a simple "hockey stick" function. Soil Sci. 166, 431–440.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61, 77–92.

Galvez, A., Sinicco, T., Cayuela, M.L., Mingorance, M.D., Fornasier, F., Mondini, C., 2012. Short term effects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties. Agric. Ecosyst. Environ. 160, 3–14.

Gao, L.W., Ma, L., Zhang, W.F., Wang, F.H., Ma, W.Q., Zhang, F.S., 2009. Estimation of nutrient resource quantity of crop straw and its utilization situation in China. Trans. Chin. Soc. Agric. Eng. 25, 173–179 (In chinese).

Ge, X., Zeng, L., Xiao, W., Huang, Z., Geng, X., Tan, B., 2013. Effect of litter substrate quality and soil nutrients on forest litter decomposition: a review. Acta Ecol. Sin. 33, 102–108.

Gholz, H.L., Wedin, D.A., Smitherman, S.M., Harmon, M.E., Parton, W.J., 2000. Long-term dynamics of pine and hardwood litter in contrasting environments: toward a global model of decomposition. Glob. Chang. Biol. 6, 751–765.

Gregorich, E.G., Janzen, H., Ellert, B.H., Helgason, B.L., Qian, B., Zebarth, B.J., Angers, D.A., Beyaert, R.P., Drury, C.F., Duguid, S.D., May, W.E., McConkey, B.G., Dyck, M.F., 2016. Litter decay controlled by temperature, not soil properties, affecting future soil carbon. Glob. Chang. Biol. 23, 1725–1735.

Guo, L., Lin, E., 2001. Carbon sink in cropland soils and the emission of greenhouse gases from paddy soils: a review of work in China. Chemosphere Global Change Sci. 3, 413–418.

Gusewell, S., Freeman, C., 2005. Nutrient limitation and enzyme activities during litter decomposition of nine wetland species in relation to litter N: P ratios. Funct. Ecol. 19, 582–593.

Hobbie, S.E., 2005. Contrasting effects of substrate and fertilizer nitrogen on the early stages of litter decomposition. Ecosystems 8, 644–656.

IPCC, 2014. Climate Change 2014 Synthesis Report. Environmental Policy Collection. 27.

Janssen, B.H., 1984. A simple method for calculating decomposition and accumulation of 'young' soil organic matter. Plant Soil 76, 297–304.

Klotzbücher, T., Kaiser, K., Guggenberger, G., Gatzek, C., Kalbitz, K., 2011. A new conceptual model for the fate of lignin in decomposing plant litter. Ecology 92, 1052–1062.

Lal, R., 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2 enrichment. Soil Tillage Res. 43, 81–107.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lal, R., 2008. Crop residues as soil amendments and feedstock for bioethanol production. Waste Manag. 28, 747–758.

Lin, H., 2014. A new worldview of soils. Soil Sci. Soc. Am. J. 78, 1831.

Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Chang. Biol. 20, 1366–1381.

Lu, F., 2014. How can straw incorporation management impact on soil carbon storage? A meta-analysis. Mitig. Adapt. Strateg. Glob. Chang. 20, 1545–1568.

Luo, Y., Keenan, T.F., Smith, M., 2015. Predictability of the terrestrial carbon cycle. Glob. Chang. Biol. 21, 1737–1751.

Manzoni, S., Piñeiro, G., Jackson, R.B., Jobbágy, E.G., Kim, J.H., Porporato, A., 2012. Analytical models of soil and litter decomposition: solutions for mass loss and time-dependent decay rates. Soil Biol. Biochem. 50, 66–76.

Nicoloso, R.S., Rice, C.W., Amado, T.J.C., 2016. Kinetic to saturation model for simulation of soil organic carbon increase to steady state. Soil Sci. Soc. Am. J. 80, 147.

Prescott, C.E., 2010. Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? Biogeochemistry 101, 133–149.

Sarmiento, J., 2000. Global change. That sinking feeling. Nature 408, 155–156.

Schmidt, M.W., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kogel-Knabner, I., Lehmann, J., Manning, D.A., Nannipieri, P., Rasse, D.P., Weiner, S., Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature 478, 49–56.

Smith, P., Fang, C., 2010. Carbon cycle: a warm response by soils. Nat. Biotechnol. 464, 499.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Glob. Chang. Biol. 6, 525–539.
Sun, W., Huang, Y., Zhang, W., Yu, Y., 2010. Carbon sequestration and its potential in agricultural soils of China. Glob. Biogeochem. Cy. 24, 1154–1157.
Tian, H., Lu, C., Ciais, P., Michalak, A.M., Canadell, J.G., Saikawa, E., Huntzinger, D.N., Gurney, K.R., Sitch, S., Zhang, B., Yang, J., Bousquet, P., Bruhwiler, L., Chen, G., Dlugokencky, E., Friedlingstein, P., Melillo, J., Pan, S., Poulter, B., Prinn, R., Saunois, M., Schwalm, C.R., Wofsy, S.C., 2016. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. Nature 531, 225–228.
Wang, C., Han, G., Jia, Y., Feng, X., Tian, X., 2011. Insight into the temperature sensitivity of forest litter decomposition and soil enzymes in subtropical forest in China. J. Plant Ecol. 5, 279–286.
Wang, X., Sun, B., Mao, J., Sui, Y., Cao, X., 2012. Structural convergence of maize and wheat straw during two-year decomposition under different climate conditions. Environ. Sci. Technol. 46, 7159–7165.
Wang, G., Huang, Y., Zhang, W., Yu, Y., Sun, W., 2015. Quantifying carbon input for targeted soil organic carbon sequestration in China's croplands. Plant Soil 394, 57–71.
Wang, J., Lu, C.A., Zhang, W., Feng, G., Wang, X., Xu, M., 2016. Decomposition of organic materials in cropland soils across China: a meta-analysis. Acta Pedol. Sin. 53, 16–27 (In Chinese).
Yousefi, A.R., Oveisi, M., Gonzalez-Andujar, J.L., 2014. Prediction of annual weed seed emergence in garlic (*Allium sativum* L.) using soil thermal time. Sci. Hortic-Amsterdam 168, 189–192.
Zhang, D., Hui, D., Luo, Y., Zhou, G., 2008. Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J. Plant Ecol. 1, 85–93.
Zhang, W., Yu, Y., Li, T., Sun, W., Huang, Y., 2014. Net greenhouse gas balance in China's Croplands over the last three decades and its mitigation potential. Environ. Sci. Technol. 48, 2589–2597.
Zhu, Z., 2008. Research on soil nitrogen in China. Acta Pedol. Sin. 45, 778–783 (In Chinese).